Current trends in preoperative, intraoperative, and postoperative care of the adult cardiac surgery patient

Cardiac surgery, now widely practiced in most parts of the world, came from humble beginnings. As late as the mid-20th century, the stigma surrounding cutting into the heart, as well as the inability to control bleeding, prevented many surgeons from exploring the field. The early operations were not without consequence. Many surgeons experienced failure, and moved on to other areas of study. But those who continued to pursue the work, would go on to make history. Today, cardiac surgery continues to grow, and encompasses many unique areas of study. It is by continuing to adapt to the needs of a changing population of patients that the specialty continues to secure its role in the future.

Current figures

It is not mandatory to report to the Society of Thoracic Surgeons (STS) National Database, but a program seeking continued recognition and reimbursement will choose to participate. From 2004 through 2013, the STS reported 2,735,459 cardiac procedures from the reporting sites.[1,2] Although overall case volume reached a peak in 2009 and began to decline the following year, there has been an increase in both isolated aortic valve replacement (AVR) and mitral valve replacement (MVR).[1,2] The unadjusted mortality rate for isolated CABG procedures over the past 10 years is approximately 2% in centers that report to the STS.[1] Isolated AVR carries an unadjusted mortality rate between 3% and 3.5%.[1] More complicated operations continue to have a higher mortality rate, with combined AVR-MVR and combined MVR-CABG procedures carrying mortality rates from approximately 8%-11% over the same 10-year period.[1]

Changes in practice, regulation, and reimbursement

Financial reimbursement for cardiac procedures has declined over the past decade. In 2003, Medicare began its pay-for-performance program, the Premier Hospital Quality Incentive Demonstration. Cardiac surgeons have been particularly affected by the Centers for Medicare and Medicaid Services cost-savings measures.[3] In the past, programs would receive the same payments for a certain procedure regardless of the outcome. Now there is a demand on hospitals to decrease complication rates. Initial studies on the Hospital Quality Incentive Demonstration did not show a reduction in risk-adjusted mortality for myocardial infarction (MI), pneumonia,

congestive heart failure, or cardiac bypass surgery despite financial incentives.[4-7] More specific to surgery is the Surgical Care Improvement Project (SCIP). This project, which is a collaboration between the Centers for Medicare and Medicaid Services and The Joint Commission, is aimed at decreasing surgical complications and focuses on several core process measures that must be met for each patient.[8] Table 1 summarizes the SCIP measures that apply to the surgical population.

In addition to SCIP, the Hospital Consumer Assessment of Healthcare Providers and Systems survey is provided to patients, within 42 days of discharge from the hospital, to evaluate their experience through the assessment of 8 categories. These 8 categories, in the order of correlation to overall satisfaction, are shown in Table 2. Hospital reimbursement is now tied to the results of such surveys.

Cardiac surgery programs' outcomes can now be referenced by the general public on the STS database website. Reporting programs strive to achieve the overall "3-star" composite score. Although the STS creates risk models for CABG, valve, and combined CABG-valve procedures, the composite scores are only calculated for isolated CABG, isolated AVR, and combined AVR-CABG, as they are 3 of the most common cardiac procedures (Table 3).

The scoring system assumes that all providers are average. A "1-star" rating means there is a 97.5% chance that any provider at the institution is less than average. A "3-star" composite score means that there is a 97.5% chance that any specific provider at an institution is better than the average. Otherwise, the institution will get a "2-star" rating.[10] Programs must continue to perform well to maintain their rating, as an increasing medically savvy public is looking to have procedures performed by those institutions with the highest ratings.

Current topics of interest

Today, CABG is among the most common operations performed in the United States. The synergy between PCI with taxus and cardiac surgery trial, which randomized patients with left main coronary disease or 3-vessel coronary artery disease, has demonstrated that CABG should remain the standard of care for this type of patient, as the study found significantly lower rates of death, MI, and revascularization, whereas stroke rates remained comparable.[11] The authors maintain that for patients with lower synergy between PCI with taxus and cardiac surgery scores, percutaneous coronary intervention (PCI) is acceptable; however, there are significantly higher rates of redo revascularization.[11]

Valve technology has seen significant advancements in recent years. Percutaneous aortic valves have been studied in populations once deemed too high risk for a traditional AVR. The placement of aortic transcatheter valves trial was a multicenter, randomized clinical trial that compared transcatheter aortic valve implantation (TAVI) with standard therapy (medical management and

Table 1
Surgical Care Improvement Project (SCIP)[8]

SCIP measure	Population
Prophylactic antibiotic received within 1 h of incision	CABG and other cardiac patients
Prophylactic antibiotic selection	CABG and other cardiac patients
Prophylactic antibiotic discontinued within 48 h after surgery	CABG and other cardiac patients
Cardiac surgery patients with controlled glucose level 18-24 h after anesthesia end time	CABG and other cardiac patients
Surgery patients with appropriate hair removal	All surgical patients
Urinary catheter removed on postoperative day 1 or 2, with day of surgery being day 0	All surgical patients
Surgery patients with perioperative temperature management	All surgical patients
Surgery patients on β-blocker therapy before arrival who received β-blocker during the postoperative period	CABG and other cardiac patients
Surgery patients who received appropriated venous thromboembolism prophylaxis within 24 h before surgery to 24 h after surgery	All surgical patients

Table 2

Categories of experiences assessed in the HCAHPS survey, in order of degree of relation to overall satisfaction[9]

Communication with nurses
Pain management
Timeliness of assistance
Explanation of medications administered
Communication with doctors
Cleanliness of room and bathroom
Discharge planning
Noise level at night

HCAHPS, Hospital Consumer Assessment of Healthcare Providers and Systems.

balloon valvuloplasty) in patients with severe aortic stenosis, who surgeons deemed not suitable for traditional aortic valve surgery.[12] This trial found that there were significantly reduced rates of death, the composite end point of death for any cause, or repeat hospitalization in the TAVI group as compared with standard therapy.[12] There was a higher incidence of major adverse cardiac and cerebrovascular events.[12] A subgroup of these patients who were deemed surgical candidates were randomized to either surgical AVR or TAVI, and the rates of survival at 1 year were found to be similar, although it should be noted that there were differences in periprocedural risks.[13]

The hybrid operating room, where cardiac surgeons and cardiologists collaborate on procedures that combine both surgical and percutaneous techniques, is a significant advancement. Minimally invasive aortic and mitral valve operations, bypass surgery, and the maze procedure are in increasing demand. There are several ways to approach the minimally invasive technique for the mitral valve such as a direct vision involving a right anteriolateral thoracotomy, the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA) for a robotic approach, or through camera-assisted techniques.[14]

AVR can also be performed with a minimally invasive approach through right anterior minithoracotomy, or by partial sternotomy. The maze procedure can be performed with bilateral or right anterior minithoracotomy.

MCS has developed into a separate branch of cardiac surgery. It is a broad and growing field, which includes everything from temporary support devices for acutely decompensated patients, to durable long-term support for patients with chronic advanced heart failure. The number of centers implanting these devices is increasing, as is the number of patients receiving devices.

Preoperative care and considerations

Risk stratification

The major computerized scoring systems used in the United States are the STS predicted risk of mortality (PROM) score and the updated European system for cardiac operative risk evaluation

Table 3

STS scoring system for cardiac surgery[10]

Components of isolated CABG composite score	Components of isolated AVR and AVR-CABG composite score
Risk-adjusted mortality	Risk-adjusted mortality
Risk-adjusted major morbidity	Risk-adjusted major morbidity
Reoperations	Reoperations
Stroke	Stroke
Kidney failure	Kidney failure
Infection of chest wound	Infection of chest wound
Prolonged use of ventilator	Prolonged use of ventilator
Use of internal mammary artery	
Use of core measure medicines	

score (EuroSCORE II).[15] The original EuroSCORE, as it has been used for the past 15 years, is no longer applicable in contemporary practice. The EuroSCORE II has been developed and has been shown to have better calibration and discrimination.[16] It retains many of the core risk factors, but includes the redefinition of the symptomatic status, and the incorporation of the creatinine clearance.[16] In addition, procedures formally listed under the umbrella "other than isolated coronary artery bypass grafting" are individually listed.[16] This gives the more complicated procedures greater weight, as is seen in the STS model.

Despite efforts to keep the scoring systems current, studies have shown their deficiencies in the current population of cardiac surgery patients. In transcatheter valve patients, the risk of mortality and morbidity is overpredicted by the EuroSCORE II.[16] Transcatheter valve patients are often older and have more comorbidities than typical cardiac surgery populations, which has driven the need for updated scoring systems. There are data to suggest that factors outside the risk models play a role in mortality and morbidity after cardiac surgery. Frailty, which is based on the speed at which an individual can walk a 5-m length, has been found to be an independent predictor of mortality after cardiac surgery and is not included in either the STS PROM score or the EuroSCORE II.[17] Chronic lung disease is part of the STS PROM risk model, but clinical judgment, rather than spirometry testing, is used to document the diagnosis.[18] A study evaluating the effect of chronic lung disease on mortality and morbidity found that chronic lung disease was better documented with spirometry testing and that this technique more accurately captured the risk associated with this disease process.[18]

The preoperative evaluation

Patients should undergo a thorough evaluation before undergoing cardiac surgery. Several preoperative conditions should be investigated before entering the operating room to avoid preventable complications (Table 4).[19]

There are numerous laboratory and diagnostic studies, which may be performed before entering the operating room (Table 5).[19]

Intraoperative care and considerations

Current trends in cardiac anesthesia

Cardiac anesthesiologists have adapted their skill set to care for the aging cardiac surgery population with more comorbidities. They have become proficient in ultrasound-guided techniques for central line placement, the use of videolarygoscopy for difficult intubations, and interpreting 3-dimensional (3D) transesophageal echocardiography (TEE).[20] A significant change over the past decade has been the withdrawal of the drug aprotinin. Cardiac anesthesiologists used this serine protease inhibitor–type antifibrinolytic for nearly all patients before 2007. A multicenter, double-blinded study called the blood conservation using antifibrinolytics in a randomized controlled trial compared full-dose aprotinin with standard dose epsilon aminocaproic acid or tranexamic acid in high-risk cardiac surgery.[21] This study was stopped early because there was a higher risk of death in the patients receiving aprotinin.[22] Controversy still remains as to whether the drug was withdrawn from the market too quickly, before a thorough evaluation was performed.

Two-dimensional TEE has been a mainstay in cardiac anesthesia, but the past 2 decades have seen an emergence of 3D echocardiographic technology. Current technology allows for more real-time imaging and better resolution.[23] The data are not clear as to whether 3D TEE adds clinical value or decreases mortality.[23,24] What is known, is that 3D TEE has superior ability to assess left and right ventricular (RV) function and is especially useful in imaging the mitral valve and in diagnosing complex mitral valve lesions.[23] It is also useful to image the left atrial appendage, as traditional 2D techniques can overread the incidence of thrombus in this structure.[23]

Table 4
Preoperative evaluation

Preoperative condition or finding	Possible effect on surgical outcome
Aortic calcification	Increased risk of stroke from calcium emboli dislodged with aortic cross-clamp
Previous chest radiation	Possible adhesions in the chest, making entry difficult
Hepatic failure	Possibility of coagulopathy after surgery
Renal failure	Possibility of need of temporary or permanent hemodialysis
Nutritional status	Poor wound healing
Bleeding disorders	Increased need for transfusion of blood and blood products
Alcohol abuse	Possible hepatic failure
Tobacco abuse	COPD may require prolonged ventilatory support
Diabetes	Poor wound healing
Neurologic symptoms	Symptoms may be magnified after surgery increasing time to recovery
Recent infections	Possibility of sepsis postoperatively or seeding of prosthetic valves with bacteria
Allergies	Systemic allergic reaction and circulatory collapse
Current medications	May be at risk of increased bleeding from antiplatelet agents, or hypotension from antihypertensives
Vein stripping	Will need to find alternate conduits in CABG surgery
Difference in the blood pressure between upper extremities	Internal mammary artery may not be suitable for a conduit in CABG patients
Poor dentition	May cause seeding of prosthetic valves with bacteria
Presence of bruits	May indicate the presence of undiagnosed peripheral vascular disease

Cardiopulmonary bypass

There have been several areas of focus where advances are being made in cardiopulmonary bypass (CPB). These advances are driven by the increase in minimally invasive operations, which have required a change in CPB technique, the continued focus on the inflammatory response associated with CPB, the subsequent efforts to decrease it, and an

Table 5
Preoperative laboratory and diagnostic studies

Preoperative laboratory and diagnostic studies	Rationale
Complete blood count	Detect chronic anemia, thrombocytopenia, or infection
Chemistry	Detect kidney disease, electrolyte abnormalities, or hyperglycemia
HgB A1C	Undiagnosed diabetes
Liver function tests	Diagnose liver disease that could affect coagulation after surgery
Coagulation studies	Detect blood coagulation disorders
Type and cross with cold screen	Ensure blood is ready for the patient if needed and check for cold agglutinins (especially important in circulatory arrest cases, where the patient temperature will get quite low)
Arterial blood gas	Diagnose underlying hypoxia or lung disease
Chest x-ray (PA and lateral in redo surgeries)	Evaluate lung fields, pleural effusions, and calcified aorta (especially important in a redo to note the number of sternal wires)
CT scan of chest	Helpful if calcified aorta is suspected on chest x-ray
EKG	Evaluate preoperative rhythm
Spirometry or pulmonary function testing	Detect undiagnosed lung disease and plan for possible difficulty weaning from the ventilator
Carotid Doppler scans	Evaluate for carotid stenosis
Urinalysis	Diagnose urinary tract infection or detect glucose in urine
CT angiogram of aorta with 3D reconstruction	Helpful in some large aortic cases

CT, computed tomography; EKG, electrocardiogram; PA, posteroanterior.

effort by surgeons and anesthesiologists to decrease the amount of blood and blood product transfusions.

CPB changed cardiac surgery for the better, but it is also a known contributor to the systemic inflammatory response syndrome (SIRS). SIRS can be described as an inflammatory process, which is no longer focused on the specific site of injury but is, instead, disseminated throughout the body.[25] SIRS can cause fever, leukocytosis, capillary leak syndrome, and multiorgan failure after cardiac surgery.[26] CPB creates several situations, which set off SIRS. The trauma of the surgery sets off cellular and humoral mediators of inflammation.[25] This is augmented by the interface of blood with the CPB circuit and the activation of compliment by CPB.[25] Myocardial ischemia, from cross-clamping and cardiac arrest, further contributes to the process.[25] Methods are being sought to decrease the activation of these processes. A multipronged approach can be used starting by testing patients preoperatively to see whether they are at risk for developing a life-threatening inflammatory response. Intraoperatively, techniques such as minimally invasive approach or off-pump CABG can be used.[25] On a cellular level, interest is being directed toward inhibiting neutrophils, platelets, and complement activation, and leukocyte depletion.[25] Mini-CPB systems are being studied, with the thought that less of the machine will interface with a patient's blood. These circuits do not include a reservoir or cardiotomy suction, have no blood-air interface, and have a smaller heparin-coated circuit.[27] The great disadvantage of these systems is that without the reservoir, they are without an air removal system, which can result in air emboli. Medical literature does not support the claim that these systems can improve patient outcomes, and they are not widely used in the United States.[27]

Retrograde autologous priming (RAP) of the CPB pump has been a major advancement in CPB technique. The principle of RAP is that the crystalloid volume of the CPB circuit is replaced with the patient's blood volume just before commencing CPB.[28] This technique has been studied by many and, although it is not new, there is new interest in it because of its role in blood conservation. As the CPB circuit is primed with the patient's blood, instead of crystalloid, there is less hemodilution, which reduces the need for subsequent blood transfusion. A meta-analysis of randomized controlled trials on the technique of RAP revealed that, although it seemed to have no effect on clinical outcomes, it did create a significant reduction in the perioperative transfusion requirements in adults.[29]

Acute normovolemic hemodilution is another technique designed to reduce the need for blood transfusion. It involves removing 1 or 2 units of the patient's blood before starting CPB to expose less of the blood volume to the CPB circuit. After terminating CPB, this blood can then be given back to the patient. Sarin and colleagues[30] demonstrated that acute normovolemic hemodilution patients received fewer intraoperative blood products, regardless of the surgery they underwent, and that the decrease in blood exposure afforded patients decreased ventilator times and postoperative mortality.

Cardioplegia used during CPB has gone through an evolution from its introduction in the 1950s.[31] Initially, it was composed mainly of crystalloid but in the 1970s, the use of blood cardioplegia gained popularity owing to the theory that it was better suited to deliver nutrients and oxygen to the ischemic heart.[31] It also reduces the edema associated with crystalloid cardioplegia and appears to offer less delay of myocardial recovery.[31] A traditional crystalloid based cardioplegia uses an 8:1 crystalloid-to-blood ratio, but newer blood cardioplegia, or microplegia, formulations have a much higher blood to crystalloid ratio. Both formulations have been studied, and the results are inconclusive. Three meta-analyses done between 2006 and 2012 are not in overwhelming favor of the use of blood cardioplegia.[32-34] Jacob and colleagues[32] reviewed 18 randomized clinical trials and found that 10 of them reported statistically significant clinical differences that favored the use of blood cardioplegia. Another study demonstrated no difference in the risk of death, MI, or low cardiac output syndrome, regardless of whether blood cardioplegia or crystalloid cardioplegia was used.[32]

The pediatric cardiac surgery community is familiar with the use of del Nido solution, which is used in several centers for myocardial protection during cardiac surgery. This solution, which is more dilute (1:4 = blood:crystalloid) than standard solutions, has less calcium and contains magnesium, mannitol, sodium bicarbonate, and lidocaine.[35] As opposed to standard cardioplegia

solution, which is generally given every 15-20 minutes, del Nido solution is usually given as a single dose.[35] It is thought that this pediatric cardiac surgery technique could be translated to the adult population. Although centers have started using del Nido solution in the adult population, current studies have failed to demonstrate an improvement in clinical outcomes. Randomized, controlled clinical trials are needed to further evaluate the data in the adult population.

Conduit harvesting in CABG

The greater saphenous vein (GSV) has long been the conduit of choice, after use of the internal mammary artery, for CABG. In the late 1990s, the traditional ankle to groin incision began to be replaced by a 2-cm incision, usually near the knee, to allow for endoscopic vein harvesting (EVH). Initial studies of this technique supported the theory that there was less surgical leg pain after the surgery, thus, allowing patients to be ambulatory earlier. It was also believed that the infection rate of GSV harvest sites was lower with a minimally invasive technique. In 2009, Lopes and colleagues[37] published a large observational study, which incidentally brought into question the safety of EVH. This study, called the project of ex-vivo vein graft engineering via transfection IV trial was actually created to study the efficacy of the oligonucleotide decoy edifoligide in preventing neointimal hyperplasia, a cause of GSV graft failure.[36] The study examined 3000 patients undergoing CABG and concluded that those who underwent EVH had a higher risk of 1-year angiographic graft failure, and higher 3-year mortality than those who underwent the open harvest technique.[37]

Despite it being an observational study, these results called into question a procedure that had become a mainstay in CABG surgery. As a counter to this study, the Food and Drug Administration (FDA) issued a request for an analysis of the STS and American College of Cardiology (ACC) Database to further assess EVH. Another large, observational study of patients undergoing isolated CABG surgery between 2003 and 2008 found no evidence of increased long-term mortality for the composite of death, MI, or revasularization associated with EVH vs open harvest technique in patients undergoing isolated CABG surgery.[38] There has been a single-center study that also demonstrated that there was a decrease in leg infections when EVH technique was used.[39]

Harvester experience and clot stranding within the GSV are often thought of as 2 confounding variables in EVH. A prospective, observational study compared open harvest technique, EVH with novice harvesters, and EVH with experienced harvesters, and assessed the veins on the fifth postoperative day with optical coherence tomography.[40] Novice clinicians (with less than 100 harvests) were far more likely than experienced harvesters (more than 900 harvests) to cause deep vessel damage during EVH.[40] Moreover, when the number of injuries to the vein surpassed 4, the risk of early graft failure rose by more than 50%.[40]

Clot stranding in the GSV is still a poorly understood phenomenon. Harvester experience, time taken to harvest the vein, heat from use of bipolar to cauterize branches, pressure exerted on the vein from CO_2 insufflation, and overinsufflation of the harvesting system obturator balloon are thought to contribute to clot stranding in GSV grafts. Administration of heparin has been studied, and giving a small dose (2500-5000 units), or full dose during vein harvesting has been reported to decrease clot formation.[41] Another study evaluated a small cohort of patients using preheparinization, and optical coherence tomography to evaluate the veins, which determined that it significantly decreased clot volume.[42]

Postoperative care and considerations

Pathways after cardiac surgery

There are 3 routes a patient can take after undergoing cardiac surgery. The first, and most preferable, track is what many institutions refer to as a fast track, or a rapid transfer. Patients who do not meet criteria for rapid progression, fall into the second category, and can be referred

to as pathway patients. The third group is defined as those patients who have fallen off the typical pathway. Modern anesthesia protocols use lower dose opiates that result in greater hemodynamic stability after surgery.[43-45] Improvements in CPB technique have decreased the damaging effects of extracorporeal circulation on the cerebral, pulmonary, renal, and hematologic systems that are traditionally associated with cardiac surgery.[46] These practices have allowed patients undergoing cardiac surgery to progress more quickly after surgery. Progressing cardiac surgery patients on a fast track has received attention because of increased pressure on health care systems to deal with an aging population, and to do so with fewer resources.[47] A prolonged stay in the intensive care unit (ICU) after cardiac surgery has been linked to a significant reduction in long-term survival, and increased use of resources and costs.[48] Fast-track protocols can vary greatly according to institution (Tables 6 and 7).

Patients who do not meet rapid transfer protocols, or pathway protocols, can have prolonged ICU stays. Studies have evaluated many variables that affect the length of stay. In a study, prior cerebrovascular accident (CVA), age, and surgeon category (a designation based on the mean hospital stay of a surgeon's patients) were independent predictors of an ICU stay greater than 48 hours.[50] Another study found 11 preoperative variables that were associated with ICU length of stay, which included emergency surgery, age, preoperative renal dysfunction, prior MI, cerebrovascular disease, type of surgery, congestive heart failure, and left ventricular dysfunction.[51]

Advances in monitoring

Over the past 2 decades, the overall use of a pulmonary artery catheter (PAC) has declined, but its use in the cardiac surgical population remains stable in many practices.[52,53] In a large, international, prospective observational study, the use of the PAC in patients undergoing CABG surgery was studied, and it was determined that those patients with a PAC had a higher risk of composite mortality and morbidity than patients without PAC.[54] The theory that the cohort of patients who received a PAC were sicker was dispelled in this study. Patients were propensity matched with central venous pressure monitoring only.[54] Therefore, those patients who had only central venous pressure monitoring fared better.[54] The increase in mortality and morbidity could be because of the more frequent and intensive hemodynamic manipulations (such as checking wedge pressures), and interventions based on the resulting data, that are associated with the use of a PAC.[54]

Because of the risks associated with the use of the PAC, Temporelli and colleagues[55] studied the use of Doppler echocardiography for hemodynamic assessment in stable patients with advanced systolic heart failure, and in potential heart transplant recipients. Their data demonstrated that Doppler echocardiography may be able to replace invasive cardiac catheterization for the measurement and monitoring of hemodynamics, and that techniques used to estimate pulmonary capillary wedge pressure (PCWP), mean right arterial pressure, and pulmonary vascular resistance showed good correlation with invasive monitoring techniques.[55] Unfortunately, cardiac anesthesiologists and cardiologists are not always available to do TEEs as needed. In response to this need, miniaturized echocardiography machines may offer less experienced clinicians a way to incorporate the benefits of ultrasound technology in a safe and

Table 6
Example of fast-track protocol[49]

Inclusion criteria for fast-track (Rabbit) protocol at Inova Heart and Vascular Institute
Ejection fraction > 35% No history of renal failure No adverse bleeding No intra-aortic balloon pump No recent neurologic events Minimal use of inotropes and pressors

If patient meets these criteria, progress on fast-track protocol and evaluate for transfer back into telemetry the evening of surgery.

Table 7
Example of fast-track protocol

Inclusion criteria for transferring to telemetry the evening of surgery
Extubated for at least 2 h
Maintain systolic blood pressure of 100 mm Hg without pressors
Neurologically intact
Off all inotropic support
In normal sinus rhythm or a sinus bradycardic rhythm that supports a blood pressure without temporary pacing (can be in atrial fibrillation if chronic and rate controlled)
Chest tube drainage less than 50 mL/h for 4 h, with the exception of a 1-time dump when sitting up
Sit on bedside with assistance and maintain hemodynamics
Maintain oxygen saturation of at least 92% on 6 L of nasal cannula oxygen or less
Results of laboratory tests within normal limits (anemia is acceptable if hemodynamically stable)

effective way. Cioccari and colleagues found that after brief bedside training, echocardiographic examinations using a miniaturized transesophageal echocardiography system (mTEE), showed good interrater ability between mTEE users, and expert cardiologists.[55]

The standard of care for respiratory monitoring in the cardiac ICU includes pulse oximetry, arterial blood gas interpretation, end-tidal CO_2, and chest radiograph. Ultrasound can also be used to diagnose a variety of respiratory conditions in critically ill patients such as pneumothorax, lung consolidation, increasing interstitial pattern, and pleural effusions.[56] This new use of old technology holds the possibility of decreasing unnecessary radiographs in cardiac surgery patients and improves providers' bedside examinations. Using ultrasonography to locate a "lung point" sign, where the visceral and parietal pleura come in contact with each other is almost 100% specific for pneumothorax, and can be used in place of additional radiography.[57]

Neurologic monitoring in the ICU setting can include sedation monitoring, brain wave monitoring, and cerebral oxygenation. Continuous sedation has been proven to correlate with worsened outcomes for most critically ill patients, making it important to tailor sedation levels for each patient's condition.[58] Sedation scales are commonly used in ICUs, the most widely tested being the Riker Sedation-Agitation Scale, and Richmond Agitation-Sedation Scale.[59-61] In addition, the use of bispectral index (BIS) to monitor processed EEG activity, and a train of 4 may be clinically relevant in the ICU setting for paralyzed patients.[62] Although there is debate surrounding the ability of BIS to monitor the depth of sedation, it is generally agreed that a BIS score of 40-60 ensures a completely sedated patient.[63,64]

Studies have confirmed that the use of transcranial cerebral oximetry, through near-infrared spectroscopy is a reliable way to detect cerebral oxygen desaturations.[65] In a cohort of moderate-to high-risk patients undergoing elective surgery using CPB, the incidence of cerebral desaturations in the immediate postoperative period was 53%, as defined by a reduction in $SctO_2$ to <60% in at least 1 oximeter sensor for at least 60 seconds.[66] It has been suggested that intraoperative cerebral hypoxia was associated with postoperative cognitive dysfunction at 3 months.[67] Postoperative desaturations may have the same effect, and more studies are needed to determine whether the routine use of cerebral oximetry monitoring in the ICU is prudent.

Mediastinal bleeding

Mediastinal bleeding in the postoperative setting requires reversal of any residual coagulopathy, while keeping stable hemodynamics. A sample protocol for correcting mediastinal bleeding, and an algorithm for administration of blood and blood products are summarized in Table 8.

Recombinant factor VIIa (rFVIIa) is another adjunct therapy for refractory mediastinal bleeding after cardiac surgery. It is FDA approved for the treatment of bleeding in patients with hemophilia A or B who have inhibiting antibodies to coagulation factor VIII or IX.[68] It is also used off-label in surgical patients with life-threatening bleeding. There has been concern over this use of rFVIIa and the risk of thrombotic events.[68] A randomized trial of patients who underwent

Table 8
Mediastinal bleeding algorithm

Corrective action	Rationale
Keep MAP at 65 mm Hg	Hypertension will exacerbate surgical bleeding
Control shivering with meperidine or paralytic and keep patient sedated	Decrease metabolic demand when HCT may already be low and decrease blood pressure
Check laboratory data, including PT, PTT, fibrinogen, CBC, functional platelet count	Diagnose and correct coagulopathy
Evaluate chest x-ray	Look for widened mediastinum or pleural effusions
Monitor hemodynamics including CVP, PA diastolic, SVO₂, and cardiac output	May help diagnose impending cardiac tamponade
Monitor urine output	May help diagnose impending cardiac tamponade
Keep patient warm (37°C)	Hypothermia impairs clotting and platelet function

CBC, complete blood cell count; CVP, central venous pressure; HCT, hematocrit; INR, international normalized ratio; MAP, mean arterial pressure; PA, pulmonary artery; PT, prothrombin time; PTT, partial thromboplastin time; SVO$_2$, mixed venous oxygen saturation.

cardiac surgery, and were bleeding, demonstrated that rFVIIa provides benefit in the treatment of post–cardiac surgery bleeding, but that an increased number of adverse thrombotic events, including stroke, occured.[69] A meta-analysis of 35 randomized clinical trials found that the use of rFVIIa in an off-label setting significantly increased the risk of arterial, but not venous, thrombotic events, especially in elderly patients.[68] These studies serve as a caution, to reserve rFVIIa for life-threatening bleeding, and not incorporate it into daily practice.

Mediastinal re-exploration in the ICU

If the corrective efforts do not produce a cessation in mediastinal bleeding, re-exploration at the bedside or the operating room is warranted. Re-exploration for bleeding increases operative mortality and morbidity, often owing to the delay in getting the patient back to the operating room, necessitating open chest resuscitation in the ICU.[70,71] Re-exploration in the ICU is associated with a high survival rate compared with emergency thoracotomy for lethal arrhythmia, or MI.[72] There is evidence that early re-exploration for bleeding may reduce blood transfusions, the risk of respiratory insufficiency, and the rate of infection for undrained hematoma.[73-75]

Mechanical circulatory support

Outside the operating room, many centers are developing protocols to provide MCS devices to the sickest patients. The intra-aortic balloon pump (IABP) continues to be a mainstay of therapy. Temporary and durable MCS devices require additional team members to support the growing number of patients living with this technology. The fifth Interagency Registry for Mechanically Assisted Circulatory Support annual report gives data on almost 7000 patients living with durable MCS devices in the United States.[76]

This number, as well as the number of centers implanting devices, continues to grow. Outcomes for survival on MCS devices continue to improve. Continuous flow pumps in bridge-to-transplant and destination therapy patients have an overall expected survival rate of at least 80% at 1 year, and almost 70% at 2 years.[77]

Intra-aortic balloon pump

IABP is the most commonly used mechanical support device in cardiac patients. It is used in 70,000 patients annually in the United States, and specifically in 5%-10% of cardiac surgery patients.[78] Complications of insertion range from the minor (eg, thrombocytopenia) to the more severe (eg, limb ischemia). Common major complications are listed in Table 9.

Table 9
Complications of intra-aortic balloon pump[78]

All cause in-hospital mortality	Mortality with IABP in place
20.1% In US institutions	10.8% In US institutions
28.7% In non-US institutions	18% In non-US institutions

Recently, the use of the IABP has faced scrutiny from the cardiac community since the publication of the Intra-aortic balloon counterpulsation in acute myocardial infarction complicated by cardiogenic shock (IABP-SHOCK II) trial. This was a randomized controlled study in which 600 patients with acute MI, complicated by cardiogenic shock, were randomized to receive IABP or nonmechanical treatment. The trial demonstrated that patients had a 30% mortality rate regardless of the use of the IABP.[79] It is intuitive that the IABP is useful in unstable revascularized patients with low cardiac output, but its use in prophylaxis is unclear.[80] There remains a need for a consensus definition of what a high-risk CABG patient is, and well-designed randomized controlled trials to better guide prophylactic IABP use.

Ventricular assist devices

Heart failure has become a global epidemic, with approximately 250,000 patients each year developing advanced heart failure, despite maximal medical therapy.[81] Because of these figures, hospital admissions for heart failure have surpassed all other diagnoses, and have created a huge national financial burden.[82] Unfortunately, for many of these patients, the treatment is heart transplantation. With a limited pool of hearts acceptable for transplant that remains well below the number of organs needed, durable MCS devices have become a viable option for many patients while they wait for transplant, with the left ventricular assist device (LVAD) being the most commonly implanted. Currently, almost 30% of patients undergoing heart transplant were supported by MCS while waiting for their organ.[83]

Historically, MCS devices provided pulsatile blood flow. Over the past decade, these pumps have, largely, been replaced with continuous flow pumps that provide either axial or centrifugal flow. Devices are used for several different indications depending on the needs of the patient. Devices placed as a bridge-to-transplant allow patients waiting for an organ to experience a better quality of life. Two prospective multicenter trials demonstrated that nearly 80% of patients on MCS lived to the time of transplant, recovery, or continued MCS with eligibility of transplant, while enjoying a fairly normal lifestyle.[84,85] There have also been encouraging results with devices placed for destination therapy. These patients are not candidates for organ transplant due to advanced age or other comorbidities or both. In this population, those with LVAD support had better outcomes than those supported with medical therapy. The 2001 randomized evaluation of mechanical assistance for the treatment of congestive heart failure trial proved that LVADs were as effective as destination therapy.[86]

A post–randomized evaluation of mechanical assistance for the treatment of congestive heart failure analysis revealed that the 1-year survival rate for patients with destination LVAD support was 61% vs 25% in those receiving medical therapy alone.[87] Temporary devices can be placed as a "bridge to decision" for hours to a few days in the setting of acute cardiogenic shock. Patients in this category are not candidates for durable support owing to poor outcomes.[81] Placing these patients on temporary support attenuates end-organ damage from cardiogenic shock and allows clinicians to better evaluate the patient for durable support. An exciting small subpopulation of patients with heart failure exists in which MCS has been a bridge to recovery. Although this represents a small number of patients, usually those with nonischemic cardiomyopathy, there are a few who experience enough improvement in their heart function to allow them to have their device explanted. A strategy of unloading the heart with an LVAD, along with aggressive pharmacologic support, improves the chances of recovery, as well as the durability of the recovery after the device is explanted.

Studies have shown that the best results are achieved in younger patients with a short history of heart failure.[88] Patients continue to have a better quality of life, when compared with transplant patients, 9 years after explantation, which shows that recovery is also long lasting.[89]

The ICU note and the electronic medical record

A system-by-system review of a patient is essential in the ICU because overlooked information can quickly become detrimental to these fragile patients. Highlighting each subsystem, and addressing any complications related to each is the most efficient way to handle the note on an ICU patient. It has been the hope of the government that the implementation of electronic medical records (EMRs) would be a way to further aid practitioners in keeping track of the large amounts of information necessary to adequately care for ICU patients. The US Department of Health and Human Services has stated that EMRs are an integral component of any future health care delivery model, and that they believe that their adoption will be a solution to system safety failures and medical errors.[90,91] There is still conflicting information regarding whether this statement is true. In the ICU setting, the adoption of an EMR has been thought to have created an information overload for clinicians, because the large amount of available data must then be processed, and the relevant information must be separated from the large amounts of extraneous data that accompany it.[92] This has led to an increased amount of research on different interfaces designed to aid practitioners in quickly and accurately processing large amounts of information.

Despite the government's interest in promoting EMRs, there have been several barriers to the acceptance of this new tool. The perception is that the adoption of an EMR requires a large learning curve and takes the clinician away from the bedside, and puts him in front of a computer.[93] In addition, because reasonable skill with typing and working with a computer are needed for success, these are also factors that must be taken into consideration. A review of 22 studies concerning barriers to physician acceptance of an EMR showed that cost, technical reasons, and time were the most commonly identified barriers.[94] EMRs are expensive to start up and maintain, and this can be a barrier in smaller institutions, or private practices. Physicians feel that EMRs take away from a patient visit because of the need to enter data into a computer. When this is done at the bedside, or in office settings, physicians feel that time spent entering data prolongs the visit, and leads to less eye contact with the patient. Although an EMR is supposed to cut down on errors, a study in the aforementioned review suggested that typos will become the new medical errors.[95] Although financial constraints and lack of computer knowledge are tangible, the ideas that many physicians have about EMRs, such as fear of record loss, and the disbelief that an EMR can improve patient care or clinical outcomes are often not backed up with statistical data.[94]

Cardiac surgery workforce and critical care

Cardiac surgery, similar to other branches of medicine, is facing a physician scarcity crisis.[96] The crisis is unique because of the extensive length of time it takes to train cardiac surgeons, the advanced age of much of the cardiac surgery workforce, and relative recent lack of popularity of the specialty.[97,98] This shortfall has already been felt in ICUs where a multitude of clinical providers care for postoperative cardiac surgery patients (Table 10).

Often, care is provided by a combination of providers, raising important questions about training and competency.[99] Surgical patients now are older and have more comorbidities than prior generations and may need prolonged critical care.[100] Innovative technology including MCS and novel surgical techniques add a further complexity to postoperative care. The medical literature is mixed on the benefit of intensivists with a single-center study citing decreased

Table 10
Providers of postoperative care

Providers providing postoperative care to cardiac surgery patients
Operative and nonoperative cardiac surgeon
Anesthesia, surgical, or medically trained intensivists
Physician assistants or acute care nurse practitioners
Cardiac surgery, general surgery, medical critical care, or anesthesia fellows
Anesthesia, surgical, or emergency medicine residents

blood product usage, decreased ICU complications, and decreased total hospital length of stay when 24-hour intensivist coverage is employed, but no change in 30-day mortality.[101] Another study showed that replacing resident coverage with advanced practice providers did not significantly alter mortality in a cardiac surgery program.[102] The combination of providers who provide care for cardiac surgery patients has changed in the last decade, but the roles of providers are being more carefully scrutinized along with their competency.[103]

Cardiac system

Hemodynamics

The stress of cardiac surgery, as well as the inflammatory process associated with CPB, can have profound effects on the hemodynamics of a patient. Low cardiac output syndrome is defined as low cardiac output with evidence of end-organ dysfunction, and it is known to increase mortality and morbidity following CABG surgery.[104,105] Initial goals of treatment should focus on maintaining a cardiac index of at least $2.0\,L/min/m^2$ or a mixed venous oxygen saturation of at least 60%, a PCWP or pulmonary artery diastolic pressure less than 20 mm Hg, and a heart rate less than 100 beats per minute through the correction of abnormal hemodynamics and laboratory values (Table 11).[106]

Vasoactive medications

An analysis of the literature on the use of inotropic and vasopressor support in the early postoperative period after cardiac surgery shows a lack of randomized prospective data to guide clinical practice.[104] In addition, there is no superior pattern of vasoactive drug use when comparing outcomes data.[104] Choices should be tailored to a patient's hemodynamics (Table 12).

Table 11
Approach to hemodynamics

Cause of hemodynamic abnormality	Corrective action
Bradycardia	Increase heart rate with temporary pacing or medical therapy
Low CVP, or PA diastolic, and low stroke volume	Replace volume
Hypothermia	Warm the patient
Elevated SVR	Replace volume or reduce afterload with medical therapy
Hypotension	Replace volume, medical therapy, or titrate vasopressors
Tachyarrhythmias	Cardioversion, defibrillation, or medical therapy
Pump failure	Review surgical procedure for possible causes, medical therapy, and IABP or mechanical circulatory support
Pericardial tamponade	Reoperation for evacuation of tamponade, or pericardiocentesis
Acidemia	Determine and correct underlying cause, and adjust ventilator

CVP, central venous pressure; PA, pulmonary artery; SVR, systemic vascular resistance.

Table 12
Hemodynamic profiles of inotropes and vasopressors used in the cardiac ICU.

Dopamine	Variable effect on SVR, chronotropy increases with dose, positive inotrope, and can increase or decrease map depending on dose
Dobutamine	Decreases SVR, strong chronotrope, positive inotrope, and variable effect on map depending on dose
Epinephrine	Variable effect on SVR, moderate chronotrope, positive inotrope, and moderate vasopressor
Milrinone	Decreases SVR, weak chronotrope, positive inotrope, and vasodilator
Isoproterenol	Decreases SVR, very strong chronotrope, positive inotrope, and can increase or decrease map depending on dose
Norepinephrine	Increases SVR, moderate chronotrope, positive inotrope, and strong vasopressor
Phenylephrine	Increases SVR, no effect on heart rate, no effect on cardiac output, and moderate vasopressor
Vasopressin	Increases SVR, no effect on heart rate, no effect on cardiac output, and strong vasopressor

MAP, mean arterial pressure; SVR, systemic vascular resistance.

Preoperative valvular disease and cardiomyopathy

Long-standing valvular disease, as well as cardiomyopathies, changes the physiology of the heart, and these patients may have heart failure before surgery. Patients with long-standing valvular heart disease have undergone physiological changes to the heart that affect its function. Echocardiography can be useful to differentiate between right-sided heart failure, left-sided heart failure, or biventricular failure, as well as diagnose systolic vs diastolic dysfunction.[107] Management strategies to optimize the hemodynamics in these types of patients are summarized in Table 13.

Arrhythmias

Arrhythmias are divided into supraventricular, ventricular, and atrioventricular (AV) blocks. Supraventricular arrhythmias are the most common after cardiac surgery, but are not frequently life threatening. Observation, drug therapy, or cardioversion is used for treatment. Ventricular arrhythmias are less common, but are often more dangerous than their supraventricular counterparts. Patients with myocardial ischemia can have reperfusion arrhythmias after bypass surgery, which necessitate pacing or blocking, as well as defibrillation.[108] First-degree AV blocks rarely require any intervention. Second- and third-degree blocks become more serious, and require intervention and either temporary or permanent pacing.

Atrial fibrillation (AF) is the most common arrhythmia after cardiac surgery. Atrial tachyarrhythmias, including AF and atrial flutter, are seen in approximately 30% of patients after CABG, 40% of patients after valve operations, and 50% of patients following combined

Table 13
Management of hemodynamics in valvular disease

Structural abnormality	Cardiac physiology	Steps to optimize hemodynamics postoperatively
Aortic stenosis	Thick, hypertrophied ventricle	Keep preload elevated and decrease heart rate
Aortic insufficiency	Dilated left ventricle	Inotropic support and IABP
Mitral insufficiency	Dilated left ventricle	Inotropic support and diuresis when hemodynamically stable
Mitral stenosis	Thickening and vasoconstriction of the pulmonary arteries	Reduce preload and heart rate
Hypertrophic obstructive cardiomyopathy	Left ventricular outflow tract obstruction	Keep preload elevated and decrease heart rate

IABP, intra-aortic balloon pump.

CABG-valve repair or replacement surgery.[109] There are several factors that contribute to the occurrence of atrial arrhythmias including trauma, stretch, or ischemia, of the atrium, epicardial inflammation, hypoxia, acidosis, electrolyte disturbances, and electrophysiological changes that accompany activation of the sympathetic nervous system.[109] The incidence of AF also increases with patients' age, to approximately 5% of people older than 65 years, and 10% of people 80 years or older.[110] It most often occurs in the second to fourth postoperative days, and has been associated with hypotension, heart failure, palpitations, and fatigue.[111] The decision as to whether to control a patient's rhythm or rate is often determined by whether the AF is new onset or permanent. Rhythm management and use of medical therapy to encourage conversion to sinus rhythm should be attempted in new-onset AF to avoid having to anticoagulate the patient. The literature does not provide the best way to accomplish this in the postoperative patient. Permanent AF has been well studied, and rate control in these patients is the first-line treatment, although there is debate as to the best therapy to accomplish this.[112,113]

Depending on the institution, first-line drugs for prevention or treatment of postoperative AF can include calcium channel blockers, β-blockers, or antiarrhythmics such as amiodarone or sololol. β-Blockers are the most extensively studied drugs in the treatment and prevention of AF, but their efficacy in the prevention of AF is only moderate in cardiac surgery patients.[114] In addition, postoperative cardiac surgery patients may be hypotensive and bradycardic, contra-indicating their use. A small prospective randomized trial demonstrated that resuming β-blockers in the postoperative period, in patients undergoing CABG and who had been taking them preoperatively, decreased the incidence and severity of AF.[115] This supports the theory that patients who stop taking β-blockers before surgery will have a rebound effect of heart rate. Clinical trials have not proven that prevention of atrial tachyarrhythmias with β-blockers reduces hospital length of stay or use of resources.[114,116] Despite the lack of definitive studies, the current American Heart Association (AHA)-ACC-European Society of Cardiology guidelines give β blocker therapy a class IA recommendation in the prevention of postoperative AF.[117] Sotalol, a class III antiarrhythmic, is an alternative drug for treatment and prevention of AF. A meta-analysis by Kerin and Jacob[111] found sotalol to be more effective in preventing postoperative AF, than either placebo or β-blockers. Its use is limited by hypotension associated with bradycardia. It is a short-acting drug, so time to load the patient is less than other alternatives such as amiodarone.[111] The AHA-ACC-European Society of Cardiology guidelines state that sotalol has not been proven effective in the conversion of new-onset or persistent AF, but that it can aid in rate control.[117] Its use is also limited by its ability to prolong the QT interval on electrocardio-gram, causing ventricular tachycardia and torsades de pointes.[117]

Amiodarone is a class III antiarrhythmic used in the treatment and prevention of AF. It can induce bradycardia, AV block, and prolong the QT interval, and carries many other extracardiac side effects.[117] A randomized, double-blind, placebo-controlled trial found amiodarone to be as effective as sotalol in converting patients into sinus rhythm.[118] The randomized controlled trial of revascularization prophylactic oral amiodarone for the prevention of arrhythmias that begin early after revascularization, valve replacement, or repair found that a 13-day perioperative course of oral amiodarone was associated with reducing the postoperative incidence of atrial tachyarrhythmias by one half.[119] This finding applied to patients both older than 65 years and younger than 65 years, in those undergoing CABG, valve repair or replacement with or without CABG, and those receiving or not receiving β-blockers.[119] Despite these studies proving the ability of amiodarone to treat AF, its side-effect profile causes many institutions to use it as a last resort.

Calcium channel blockers, such as diltiazem, are a reasonable choice for the rate control of AF, especially in patients with left ventricular dysfunction, as they have less of a negative inotropic effect than β-blockers. There is no evidence to support the antiarrhythmic effects of calcium channel blockers; however, they will aid in rate control.[117] There is a study that showed that diltiazem decreased the amount of AF episodes in a 3-month period by 50%.[120]

Ventricular arrhythmias after cardiac surgery are worrisome, and require prompt intervention. Coronary artery disease, structural heart disease, and left ventricular dysfunction were found to predispose patients to malignant ventricular arrhythmias.[121] In 2012, the largest analysis to date of the incidence, predictors, and outcomes of postoperative ventricular

arrhythmias was performed, and it found that increased age, lower ejection fraction, need for emergency surgery, and peripheral vascular disease were 4 predisposing factors for ventricular arrhythmias.[122] Drugs such as amiodarone and lidocaine can also be used as adjunct therapy. Treatment and prevention are key, as patients with postoperative ventricular arrhythmias were shown to have an increased risk of in-hospital mortality.[122]

Complete heart block and bradyarrhythmias may be seen more often in the ICU given the increase in transcatheter valve implants. These patients are spared the effects of CPB, but they have their own unique set of sequelae. It is assumed that the conduction system impairment that occurs with transcatheter valves is due to the compression of a smaller annulus by a large valve prosthesis, along with compression from the calcified masses that are left in the aortic annulus.[123] Bleiziffer and colleagues[123] studied this phenomenon in an attempt to determine whether there were any risk factors for the development of new-onset AV block requiring pacemaker. Of 159 patients undergoing transcatheter valve placement, 44 required insertion of permanent pacemaker for new-onset high-grade AV block, sick sinus syndrome, or bradycardia.[123] They found that patients with a native valve annular size at the lower end of the recommended size for the prosthetic valve had an increased risk of needing a pacemaker.[123] This must be balanced with the risk of prosthesis migration or perivalvular leak, if the smaller prosthesis is chosen.[123] Patients who instantly went into AV block in the operating room had an almost 5-fold risk to develop permanent AV block, which required a pacemaker.[123]

Pulmonary hypertension

A tremendous growth in knowledge and treatment of pulmonary hypertension (PH) has occurred over the last decade, but a full analysis is beyond the scope of this review. PH Network is classified into 5 groups, with cardiac surgery patients being mostly in group 2, secondary to left ventricular disease.[124] The effect of PH was examined in AVR patients with preoperative PH who, according to a single-center 13-year retrospective study, had higher operative mortality (9% vs 5%), longer ventilation times, and significantly lower 5-year survival rates for patients with severe PH.[125] Researchers have raised concerns that cardiac surgery preoperative risk factor scoring systems may not adequately account for the operative risk incurred in patients with PH.[126] It appears that the absolute value of the pulmonary arterial pressure is less important than the RV adaptation to it.[127] If the RV is maladaptive, patients can have hemodynamic collapse, and pharmacologic therapy is needed. Inhaled nitric oxide is the best studied pulmonary vasodilator, but inhaled prostacyclin and prostacyclin derivatives are also used.[128] Randomized clinical trials are needed to determine optimal timing, dosing, and choice of agents for cardiac surgery patients.

Pulmonary system

Pulmonary complications occur in up to 20.5% of cardiac surgery patients, with ventilation longer than 24 hours, pneumonia, pulmonary embolism, and pleural effusions necessitating drainage being reportable to the STS. Patients can be categorized according to the three phases of surgery (Table 14).

Preoperative risk

The STS PROM score and the EUROSCORE II both use the presence of chronic lung disease as a risk factor for postoperative morbidity and mortality. Neither scoring system uses pulmonary function tests relying, instead, on a patient's medical history of chronic obstructive pulmonary disease (COPD), which can be incorrect in more than 30% of cardiac surgery patients.[129-131] Adabag and colleagues[129] found that patients with forced expiratory volume in 1 second/forced vital capacity <0.7, forced expiratory volume in 1 second <79%, and carbon monoxide diffusing capacity <50% have 10 times higher risk of mortality after cardiac surgery vs patients with mild

Table 14
Pulmonary considerations

Preoperative (risk assessment)	Intraoperative (injury may occur, creating a complication)	Postoperative (complications are recognized and treated)
Identify patients at risk Document preoperative lung disease	Anesthetic effects Surgical technique Effect of surgically induced hypothermia Effect of cardiopulmonary bypass	Atelectasis Pleural effusions Pneumonia Pulmonary embolism ARDS Ventilator weaning

pulmonary function tests abnormalities. A randomized controlled trial comparing CABG outcomes in patients with COPD using CPB vs off-pump CABG showed that patients had similar 30-day and 1-year mortality rates. After propensity matching, the study found that patients with COPD required more reintubations and stayed on the ventilator longer than 48 hours more often than patients without COPD.[132]

Intraoperative injury

During anesthesia, functional residual capacity decreases by as much as 20% in healthy volunteers, and patients with lung disease have more risk of developing pulmonary morbidities postoperatively.[133] The choice of surgical site can affect postoperative respiratory function because postoperative pain can diminish pulmonary inspiratory effort. Median sternotomies change pulmonary mechanics, which can decrease patients' vital capacity for up to 4 months postoperatively.[134,135] Anterior lateral thoracotomies are reportedly more painful than median sternotomies and require more postoperative analgesia, but neither site appears to affect long-term pulmonary outcomes for CABG patients.[136]

The incidence of phrenic nerve injury is unclear, with studies citing between 10% and 73%, likely owing to the sensitivity of diagnostic testing. Many patients fully recover the function of the nerve with time.[137] The injury appears to be caused by hypothermia during CPB, as the nerve courses over the pericardium and is subjected to cold cardioplegia and ice. Postoperatively, the diagnosis of phrenic nerve injury can be made using bedside ultrasound, fluoroscopy, or electrophysiology.[138] Left lower lobe atelectasis, which is common after cardiac surgery, may be secondary to phrenic nerve injury, inadequate pulmonary clearance, lung collapse, lack of use of positive end-expiratory pressure during surgery, pulmonary endothelial damage due to cardioplegia solution, and longer duration of CPB.[139]

Inflammation from CPB can lead to postoperative pulmonary morbidity. The ischemic lung hypothesis postulates that the lungs are not part of the systemic circulation during CPB, and that blood flow in the lungs is static as bronchial circulation only accounts for a maximum of 5% of blood flow to the lungs. As a result, an increase in pulmonary lactate occurs, signifying the ischemia.[140] In the SIRS, monocytes, macrophages, lymphocytes, and endothelial cells are activated. The lungs withstand the worst of the inflammatory cascade set off by CPB, as they are filters for the body's cardiac output.[140]

Strategies to limit lung injury during CPB are summarized in Table 15. The mechanism of lung injury remains an active area of research.[141] Before 2012, a significant practice difference existed between cardiac surgery centers owing to a lack of literature about the use of prophylactic steroids to blunt the inflammatory cascade associated with CPB.[142] This is partially due to the dexamethasone for cardiac surgery (DECS) trial, which was a randomized controlled study using a single dose of prophylactic dexamethasone (1 mg/kg), which did not show statistically significant benefit in the primary end points of death, MI, or respiratory failure within 30 days.[143] Despite these findings, there were fewer patients who required postoperative ventilation greater than 24 hours in the steroid group vs the placebo group (4.9% vs 3.4%).

Table 15
Strategies to limit lung injury during CPB

Intervention	Mechanism of action
Off-pump surgery	Reduced cytokine and SIRS response
Drugs (steroids)	Reduced proinflammatory cytokine release
Biocompatible circuits	Mimics endothelial surface and reduces complement activation and inflammatory response
Leukocyte filters	Preferentially removes activated leukocytes, and attenuates ischemia and reperfusion injury
Ultrafiltration	Removes destructive and inflammatory substances, and reduces SIRS response
Protective ventilation strategies	Prevents atelectasis and pulmonary ischemia
Pulmonary perfusion techniques (ie, Drew-Anderson technique)	Continuously perfuses the lungs
Meticulous myocardial protection	Avoid use of oxygenator, reduced proinflammatory cytokines, and limit ischemia-reperfusion injury to lungs

Complications in the postoperative period

The most common postoperative complication is atelectasis, occurring in 54%-92% of patients.[144] Treatment includes encouraging good pulmonary hygiene, incentive spirometry, chest physiotherapy, noninvasive ventilation, and high-flow nasal cannula oxygen.[144,145] Pleural effusions requiring drainage (independent of technique) occur in 3.4% of isolated CABG patients, 4.9% of isolated AVR patients, and 6.9% of combined CABG and AVR patients.[2] The risk factors for effusions that persist longer are not clear, but have been studied. A study found a significant relationship between pleural effusion and sex (women), preoperative diagnosis of heart failure, AF, preoperative diagnosis of peripheral vascular disease, and receiving therapy with an anticoagulant or antiarrhythmic agent.[146] However, many of these relationships disappeared when a multivariate analysis was performed.[146] The use of bedside point-of-care lung ultrasound by medical providers decreases patients' radiation exposure from radiographs, reduces complication rates from drainage procedures, and decreases the associated risk of transport.[147-149]

The most significant postoperative pulmonary complication is acute respiratory distress syndrome (ARDS), owing to its mortality of up to 40%.[150] The definition for ARDS was changed in 2012 to the Berlin criteria, eliminating the term "acute lung injury" (ALI) and, instead, creating categories defining the severity of ARDS (Table 16).[151] The need for the PCWP and the incorporation of positive end-expiratory pressure have been eliminated. This change reduces the clinical subjectivity in the diagnosis of ARDS and allows accumulated clinical data since the previous American-European Consensus Conference 1994 definition to be incorporated into the new definition.[152]

An 8-year retrospective analysis of more than 6000 cardiac surgery patients found an incidence of ARDS of 0.61%, with transfusion of greater than 3 packed red blood cells, complex cardiac surgery, and previous cardiac surgery as the only risk factors for developing the disease.[150] The cornerstone of treatment for ARDS remains low tidal volume ventilation with goal plateau pressures less than 30 mm Hg, but recent progress has been made in decreasing mortality with other interventions including the proning, or turning face down, of patients.[153-155] Transfusion-related ALI occurs within 6 hours of infusion of plasma containing transfusion and causes ALI.[156] The incidence in a cardiac surgery population in a study was 2.4%, but is likely higher owing to underreporting.[157] This complication has an associated mortality rate of 13%.[157] This association is important, because the transfusion requirements after cardiac surgery trial, a 500-patient randomized controlled trial showed no benefit to a liberal packed red blood cell transfusion strategy in a cardiac surgery population.[158]

Amiodarone toxicity is a rare cause of ARDS, but can cause pulmonary toxicity in 5%-10% of the general population, with a mortality rate of 10%-23%.[159] The risk factors of lung toxicity have been reported to be elderly age, duration of treatment, and total cumulative dosing of

Table 16
The Berlin definition of acute respiratory distress syndrome[152]

Components of the diagnosis	Needed to fit the Berlin definition
Timing	Within a week of a new insult, or increased respiratory symptomatology.
Chest x-ray or CT scan	Must show opacities bilaterally not explained by effusions, atelectasis, or nodules.
Origin of edema	Edema or respiratory symptoms not fully explained by a cardiac source, or by fluid overload. Objective assessment needed.
Oxygenation (at altitudes <1000 m)	
Mild	200 mm Hg $< PaO_2/FiO_2 \leq$ 300 mm Hg with PEEP or CPAP $\geq$ 5 cm H_2O
Moderate	100 mm Hg $< PaO_2/FiO_2 \leq$ 200 mm Hg with PEEP $\geq$ 5 cm H_2O
Severe	$PaO_2/FiO_2 \leq$ 100 mm Hg with PEEP $\geq$ 5 cm H_2O

CPAP, continuous positive airway pressure; FiO_2, fraction of inspired oxygen; PaO_2, partial pressure of arterial oxygen; PEEP, positive end-expiratory pressure.

amiodarone. Treatment involves supportive care with possible benefit from treatment with steroids, as well as withdrawal of the drug itself.[160]

Gastrointestinal system

Routine care of the gastrointestinal (GI) system after cardiac surgery consists of an orogastric tube for medication administration and management of gastric secretions in the intubated patient. A literature review reveals an incidence of GI complications of less than 1%-4%.[161-163] Mortality rates vary from 13.9%-63%.[164-166] There has been speculation that off-pump surgery reduces GI complications; however, several studies have shown similar rates of mesenteric hypoperfusion, as well as complication and mortality rates.[167-169] Vasoconstriction, decreased perfusion from low cardiac output or hypotension, and hypoxia during CPB or in the postoperative period predispose the bowel to dysfunction.[170,171] Impaired small intestinal transport, increased gut permeability, preoperative fasting, and use of anesthetics and opioids are also contributors.[172-174]

Dysphagia

Dysphagia after cardiac surgery is often related to the use of TEE.[175,176] Additional independent risk factors are age, diabetes, stroke, impaired myocardial function, longer intubation, tracheostomy, and duration of surgery.[176] TEE is also an independent risk factor for the development of postoperative dysphagia. A prospective randomized trial studying TEE examination postulated that removing the TEE probe after initial examination and replacing it after CPB would decrease postoperative dysphagia.[177] The study demonstrated that the length of time the TEE probe was in contact with the esophagus was an independent predictor of postoperative dysphagia, and that dysphagia could be reduced by removing the TEE probe for the duration of the surgery.[177] In this series, reinsertion of the probe was not associated with any esophageal complications.

Upper GI bleeding

GI bleeding is one of the most common complications of the GI system after cardiac surgery.[178] Risk factors include advanced age, diabetes, renal failure, cerebrovascular disease, postoperative low cardiac output, and CPB time greater than 98 minutes.[179,180] Most institutions include GI prophylaxis in their postoperative regimen. Studies on the efficacy of prophylactic agents, including mucosal protectants, H_2 receptor antagonists, and proton pump inhibitors (PPIs), are conflicting. PPIs have been shown to work better in high-risk patients, but they carry

the association of possible *Clostridium difficile* infection and an increase in ventilator-associated conditions (VACs). Routine prophylaxis with sucralfate during the initial intubation period is low risk, and may provide protection against decreased perfusion to end organs and coagulopathy during low cardiac output states.[181]

Treatment of bleeding includes a nasogastric tube and administration of PPIs in intravenous (IV) bolus or continuous infusion.[182] Administration of this class of medicine has been found to have better results than H_2 receptor blockers.[183] Major bleeding will require transfusion of packed red blood cells. Anticoagulation should be held and reversed, in the setting of significant bleeding. Upper endoscopy should be used in patients not responsive to medical therapy.

Lower GI bleeding

Risk factors specific to lower GI bleeding are diverticulosis, cancer, ischemic bowel, anorectal disorders, *C. difficile*, and angiodysplasia.[184] Initial treatment involves diagnosing the underlying cause, replacing lost blood, and reversing anticoagulation. Refractory bleeding should be explored with colonoscopy.[185] If colonoscopy fails to provide a source, or cannot be performed, angiography, and then radioisotope scans, should then be employed in a stepwise fashion.[184] Embolization of the bleeding source, injection, or thermocoagulation during endoscopy will likely be able to alleviate bleeding.[184] Surgical consultation for colectomy is a last resort.

Ischemic bowel

Despite advances in imaging and critical care management, ischemic bowel is still associated with a mortality rate of 50%-100%.[178] Risk factors include advanced age, prolonged time on CPB, use of IABP, high level of inotropic support, peripheral vascular disease, emergency surgery, and postoperative renal failure.[186-188] Patients with extensive bowel infarct will have severe metabolic acidosis, and this diagnosis must be excluded in those who present this way.[178] Aggressive treatment with mesenteric angiogram or exploratory laparotomy should occur if peritonitis, sepsis, or end-organ failure occur in a patient with clinical suspicion for intestinal ischemia.[189]

Hepatic dysfunction and failure

Asymptomatic transaminitis, elevation of the total bilirubin level, and alkaline phosphatase level are common after cardiac surgery. As many as 25% of patients will experience temporary hyperbilirubinemia, as defined by a total bilirubin greater than 3 mg/dL, but less than 1% of these patients will experience significant hepatocellular dysfunction that will progress to chronic hepatitis or hepatic failure.[190,191] Although the mortality rate of hyperbilirubinemia is 4%, a literature review found the mean mortality rate of actual liver failure to be 56%.[178] Causes of perioperative liver dysfunction include preoperative heart failure and resulting liver congestion; hemolysis from CPB, the use of operative field suction, or prosthetic valves; blood transfusion; hypoxia; or reperfusion injury.[178]

Management of patients with liver dysfunction will depend on the clinical picture. The asymptomatic patient with mild elevation of liver function tests can be managed conservatively by withdrawing hepatotoxic drugs such as statins and acetaminophen, and monitoring laboratory values. Patients with elevated enzyme levels on liver function tests and whose abdominal examination have abnormal findings should be further evaluated for biliary pathology with a right upper quadrant ultrasound. For patients with perioperative cardiogenic shock and resulting shock liver, further treatment may be required. These patients will often have coagulation abnormalities that may need to be treated with the supplementation of clotting factors, if there is significant bleeding postoperatively.

Research on patients undergoing cardiac surgery with known liver failure from cirrhosis is limited. These patients represent a population at significant risk of perioperative complications.

Liver failure is often staged using the Child-Pugh score. The Model for End-stage Liver Disease score is used to predict 3-month mortality (Table 17).

A small but interesting retrospective cohort study sought to evaluate clinical outcomes on patients with advanced liver cirrhosis, as defined by Child-Pugh class B or C, who underwent cardiac surgery using a liver protective strategy.[192] The cohort had a Model for End-stage Liver Disease score of 3-19. This group preoperatively treated malnutrition, sodium retention, ascites, and hyperammonemia, as well as managed preoperative coagulopathy with vitamin K, platelets, and fresh frozen plasma. Intraoperatively, they were treated with steroids, and prostaglandin, avoided low flow states, kept a hematocrit of 25%-30%, ensured appropriated drainage, treated tricuspid regurgitation, and used ultrafiltration to remove excess fluid. With this protocol in place, the authors postulated that, although redo surgery carried a high mortality rate of 50%, cardiac surgery could safely be performed on select patients with advanced liver failure.[192]

Renal system

Postoperative acute kidney injury (AKI) is a poorly understood phenomenon, but one that can have dramatic consequences for patients. The incidence of AKI in cardiac surgery patients is wide, occurring in 3%-30% of patients, with dialysis required in 1%-5% of patients, and associated mortalities in more than 60%.[193] The incidence of AKI after CABG is less, approximately 1%-2%, with lower need for dialysis, and significantly less associated mortality.[194] Independent of the type of cardiac surgery, AKI portends increased morbidity and mortality, but treating the disease has been difficult due to variable definitions of AKI and different predictive scoring systems.[193] In an effort to standardize the disease process the AKI Network was created to evaluate renal function within 48 hours of injury, and to encourage researchers and clinicians to reduce the variability in describing renal dysfunction.[195]

The variability in describing renal dysfunction is almost rivaled by the number of predictive post–cardiac surgery AKI scoring systems. The most widely validated system is from a single high-volume cardiac surgery center in which more than 30,000 patients were examined.[193] The authors used a weighted point system for the risk factors and higher scores were associated with an increased incidence of renal failure (Table 18).[196]

Considerable effort has gone into trying to prevent renal failure, with much attention focused on N-acetylcysteine. N-acetylcysteine blunts the inflammatory cascade produced by hemodynamic changes incurred during cardiac surgery, but it does not reduce the incidence of postoperative AKI.[197] Fenoldapam has shown promise in reducing the incidence of

Table 17
Classification schemes for liver failure[192]

Scoring system	Components	Scoring
Child-Pugh	Degree of ascites, serum total bilirubin level, INR, and degree of encephalopathy	1-3 Points for each component depending on severity Class A = 5-6 points Class B = 7-9 points Class C = 10-15 points
MELD	Serum total bilirubin level, INR, and serum creatinine level	$X \text{Log}_e$ (bilirubin) $+ 11.2 \, X \text{Log}_e$ (INR) $+ 9.6 \, X \text{Log}_e$ (creatinine) <9 = 1.9% Mortality 10-19 = 6% Mortality 20-29 = 19.6% Mortality 30-39 = 52.6% Mortality 40+ = 71.3% Mortality

INR, international normalized ratio, MELD, model for end-stage liver disease.

Table 18
Acute renal failure scoring system (minimum score = 0 and maximum score = 17)[196]

Risk factor	Points
Female sex	1
Congestive heart failure	1
Left ventricular ejection fraction <35%	1
Preoperative use of IABP	2
COPD	1
Insulin-requiring diabetes	1
Previous cardiac surgery	1
Emergency surgery	2
Valve surgery only (reference to CABG)	1
CABG and valve surgery (reference to CABG)	2
Other cardiac surgery	2
Preoperative creatinine 1.2-2.1 mg/dL (reference to 1.2)	2
Preoperative creatinine >2.1 mg/dL (reference to 1.2)	5

IABP, intra-aortic balloon pump; CABG, coronary artery bypass graft; COPD, chronic obstructive pulmonary disease.

dialysis-dependent AKI in postoperative cardiac surgery patients by vasodilating the renal vasculature, but more data are required.[198,199] No pharmacologic therapy has been proven through a well-designed randomized controlled trial to be effective in preventing postoperative AKI.[198] A beneficial nonpharmacologic measure is the postponement of cardiac surgery after administering contrast dye for coronary angiography (and also computed tomography scan IV contrast agent) in patients with preoperative AKI, as this decreases the incidence of postoperative AKI.[200] CPB has well-known effects on the kidneys including the release of cytokines and vasoactive hormones, which may influence AKI. Coronary artery bypass patients with preoperative AKI have a slightly better chance of avoiding dialysis if the operation if performed off-pump.[201] The only 2 known modifiable variables that can decrease the incidence of postoperative AKI are CPB time and the administration of a contrast agent.[202]

Once AKI has occurred, patients may benefit from a nephrologist's evaluation to determine the cause of their dysfunction and the optimal treatment. If dialysis is needed, patients have a significant increase in mortality rate.[203] Patients who are hemodynamically unstable are often treated with continuous renal replacement therapy, but no benefit in mortality rate has been observed in the general critical care population, with the recognition that studies suffer from significant heterogeneity.[204]

Neurologic system

Neurologic concerns after cardiac surgery can be divided into stroke, peripheral neuropathies, and encephalopathy. Defining the actual rate of stroke after cardiac surgery can be difficult as there is wide variation depending on the patient's risk factors, type and length of surgery performed, and the criteria used to diagnose the infarct. When radiographic evidence of infarct is included in the diagnosis criteria, the incidence of stroke increases by a factor of 10, with inclusion of magnetic resonance imaging yielding the highest rates.[205] Preoperative risk factors such as advanced age, prior stroke, hypertension, diabetes, anemia, and postoperative AF also play a role.[205-207] A recent study reported an overall stroke rate to be 1.6% after isolated CABG.[208] The STS 2013 data (Q1-Q3) breaks down the postoperative stroke rate according to procedure (Table 19).

Stroke

The exact cause of stroke after surgery is poorly understood. Microembolization of aortic plaque after cross-clamping certainly plays a role, but there are also data to suggest that hypoperfusion and the systemic inflammatory response may also be sources of neurologic

Table 19
Stroke rate for various operations

Isolated CABG	Isolated AVR	AVR + CABG	Isolated MVR	MVR + CABG	Mitral repair
1.3%	1.4%	2.2%	2%	3.5%	1.3%

injury.[209] The fact that off-pump CABG, where the aorta is not cross-clamped, does not clearly decrease stroke rate, further illustrates this point. A review of multiple randomized trials has not shown decreased rates of postoperative stroke after off-pump CABG.[205] Other nonrandomized studies have demonstrated that off-pump CABG was associated with fewer early strokes, but that delayed stroke rates were the same.[210]

There are several proposed management strategies aimed at reducing perioperative stroke. Patients undergoing CABG now almost routinely receive statin medications, but their role in reducing stroke risk after surgery remains controversial, and evidence is limited to observational studies.[205] A study suggested a decreased stroke rate with the use of preoperative statin and β-blockers, but this is not supported by a large body of evidence.[211] Many centers have started using intraoperative epiaortic ultrasonography to locate plaque in the aorta before applying the aortic cross-clamp. This technology allows the surgeon to attempt to place the clamp in a way that it will not disrupt intra-aortic plaque. Observational studies have shown that this technique reduces stroke rates; however, this has not been proven in randomized clinical trials.[208,212] Near-infrared spectroscopy can be used to monitor cerebral oxygenation and show adequacy of tissue perfusion, but this also has also not been tested in randomized clinical trials.[205] Routine screening of the carotid arteries before surgery is a common practice. It is not clear, however, what should be done with the information once a patient has been found to have significant ($>60\%$) carotid artery stenosis. A recent nonrandomized study showed an increase in the rate of stroke in patients who underwent combined CABG-carotid endarterectomy, as compared with patients who had the same degree of carotid artery stenosis and underwent CABG alone.[213]

Peripheral neuropathies

Peripheral neuropathies after cardiac surgery can be seen in the upper extremities, with diaphragmatic dysfunction from phrenic nerve injury, or in the injury of an intercostal nerve. Many of these abnormalities will resolve in a few weeks to months; however, a study on intercostal nerve damage showed that 15% of patients were still symptomatic 5-28 months after operation.[214] A more serious concern is injury to the phrenic nerve, which causes diaphragmatic dysfunction. This has been noted in 10%-20% of patients following cardiac surgery, depending on the series.[137,138,215] Patients who have injury bilaterally will often need long-term ventilator support.

Encephalopathy

Encephalopathy is a broad term often used to describe conditions such as confusion, delirium, altered mental status, agitation, and combativeness. The incidence of postoperative encephalopathy varies widely from 8.4%-32%, depending on the series.[216,217] Delirium is discussed frequently in the literature, and is associated with an increased length of stay and higher mortality rates.[206] Its causes are not completely understood, but are thought to be related to microemboli and hypoperfusion during CPB. Preoperative risk factors include prior stroke, hypertension, diabetes, presence of a carotid bruit, and age.[206] Postoperative factors also have a role. Delirium is categorized into the motor subtypes of hyperactive, hypoactive, and mixed (altering between lethargy and agitation).[218] Studies have shown that hypoactive delirium is the most common motor subtype in geriatric (age >50 years) patients and that it is associated with a higher 6-month mortality rate.[219,220] It has also been linked with a longer ICU stay, and a longer duration of mechanical ventilation in postoperative cardiac surgery patients.[221]

Postoperatively, the use of narcotics and benzodiazepines can have a negative effect on delirium. Patients receiving benzodiazepines before admission to a medical ICU developed delirium within the first 48 hours of stay.[222] Haloperidol is frequently used in the ICU setting to treat delirium. Its use is based on limited data.[223,224] No randomized placebo-controlled trial exists to support the use of haloperidol in critically ill patients or prove that it decreases the symptoms or duration of delirium.[224] There is promising research on the drug dexmedetomidine. A randomized clinical trial compared the use of dexmedetomidine with propofol in cardiac surgery patients and found that patients sedated with dexmedetomidine had a significantly lower rate (3% vs 50%) of delirium than those given propofol.[225] The randomized controlled trial DEXmedetomidine COmpated to Morphine compared dexmedetomidine with a morphine regimen and found that it reduced the duration, but not the incidence, of delirium after cardiac surgery.[226]

Endocrine and metabolic system

Diabetes and glucose control

It is known that patients with diabetes are at risk for coronary artery disease; however, diabetic patients make up less than 50% of the population in most cardiac surgery centers.[227] Hyperglycemia due to the stress of surgery is commonly seen in the cardiac ICU. It has been associated with increased perioperative morbidity and mortality.[227]

Initially, recommendations for glucose control were largely based on a study that advocated strict glucose control (90-120 mg/dL) in the ICU.[228] The Portland Diabetic Project, a large, prospective, observational study, found that hyperglycemia in the first 72 hours after cardiac surgery was an independent predictor of mortality, deep sternal wound infection, and an increased length of stay.[229] The authors also advocated a 3-day IV insulin infusion after cardiac surgery, after finding that it eliminated the increased risks of these 3 complications in the diabetic population.[229] A 2004 study of diabetic patients demonstrated that a glucose range between 120 and 180 mg/dL was safer than strict control in diabetic patients undergoing cardiac surgery, but that this more liberal range did not lead to improved outcomes.[230] In 2009, the normoglycemia in intensive care evaluation-survival using glucose algorithm regulation trial actually found that strict glucose control (81-108 mg/dL) increased 90-day mortality rate when compared with a liberal glucose (<180 mg/dL) range.[231] However, this study was mainly comprised of nonoperative patients with sepsis or multisystem organ dysfunction and not cardiac surgery patients.

The consensus is that hyperglycemia should be avoided, and that hypoglycemia is harmful, but the optimal glucose in a postoperative cardiac surgery patient has been difficult to define. To answer this question, Desai and colleagues[227] conducted a prospective, randomized, controlled trial to test the theory that a liberal glucose range (121-180 mg/dL) was not inferior to a strict glucose range (90-120 mg/ddL) for outcomes in patients after first-time isolated CABG.[229] Their research demonstrated that the liberal glucose range led to similar outcomes when compared with the strict range, and that the liberal range was superior in glucose control and target range management.[227] Based on a series of clinical trials, the STS currently recommends this same liberal range for postoperative cardiac surgery patients in the ICU, and that the most efficient way to achieve a glucose target range is with an insulin infusion (level A).[227,230,232]

Hematologic system

Aspirin therapy

It is well known that aspirin decreases mortality and ischemic events in coronary artery bypass surgery patients. Aspirin is also shown to improve coronary artery bypass graft patency, and decrease the incidence of stroke, renal failure, and bowel infarction.[233,234] Despite this

evidence on the benefits of aspirin therapy, conflicting opinions remain regarding discontinuation of aspirin before cardiac surgery. Multiple major medical societies, including the AHA, STS, ACC, and the European Association for Cardiothoracic Surgery, have not agreed on a stop time for preoperative aspirin. A reason for the controversy is that several randomized clinical trials have shown that aspirin given before coronary artery surgery with CPB causes increased postoperative bleeding and the need for blood transfusion.[235] The STS practice guidelines recommend stopping aspirin therapy 3-5 days before elective CABG surgery.[235] This is based on a review of the literature which found that 5 of the 6 randomized controlled trials determined that aspirin increased blood loss as measured by chest tube drainage, increased blood transfusion rates, or increased the frequency of mediastinal re-exploration.[235] Additionally, in randomized trials of patients undergoing CABG, preoperative aspirin administration resulted in 200-400 mL of increased chest tube drainage, and between 0.5 and 1 unit of increased packed red blood cell transfusion, when compared with controls.[235]

Clopidogrel

The thienopyridine, clopidogrel, inhibits platelet aggregation by blocking the effects of adenosine diphosphate at its receptor, which inhibits adenosine diphosphate–mediated activation of the glycoprotein IIb/IIIa receptor. Despite the development of new novel oral anticoagulants, clopidogrel maintains a role in the treatment of cardiac surgery patients. It is FDA approved to decrease thrombotic events after acute MI, cerebrovascular accident, established peripheral arterial disease, non-ST segment elevation MI, and acute coronary syndrome in ST segment elevation MI. Most studies demonstrate that when clopidogrel is given within 5 days of surgery, there is an increased risk of bleeding, an increase in blood transfusions, and an increase in the need for re-exploration for bleeding.[236-239]

Clopidogrel has 2 important roles in the postoperative setting. It should be given to patients who cannot take aspirin, starting with a load of 300 mg, and then 75 mg daily to prevent inadequate platelet inhibition in the first several days.[240] It is also important in patients following off-pump surgery, and its early institution reduces cardiac events, and does not increase the risk of bleeding.[241]

Continued role of unfractionated heparin and low-molecular-weight heparin

Unfractionated heparin (UFH) and low-molecular-weight heparin (LMWH) are both antithrombin activators that inhibit factors Xa and IIa. They are frequently used in the postoperative setting for venous thromboembolism (VTE) prophylaxis, and bridging therapy in valve replacement patients. Owing to its short half-life and ease of titration, UFH is still the drug of choice for patients on extracorporeal membrane oxygenation, and for bridging therapy in patients with other MCS devices. Some would advocate that IV UFH is best monitored by anti-Xa heparin assay, rather than the traditional monitoring with activated partial thromboplastin time. Guervil and colleagues[242] found that monitoring the anti-Xa heparin assay achieved therapeutic anticoagulation more rapidly and maintained the values within the desired goal range for a longer period of time.

A controversial topic is routine prophylaxis against VTE following cardiac surgery.[243] A conventional thought is that VTE may be less clinically significant in the postoperative cardiac surgery patient, as these patients have been exposed to intraoperative heparin, and that the resultant platelet dysfunction and hemodilution following surgery provide a protective effect against VTE.[244] This theory remains unsubstantiated, as there are currently no randomized clinical trials that specifically address the effect of thromboprophylaxis in patients after cardiac surgery.[237] The American College of Chest Physicians recommends that patients undergoing CABG receive VTE prophylaxis with LMWH, low-dose UFH, or intermittent pneumatic compression devices.[245] CABG patients who are at high risk for bleeding should receive prophylaxis with intermittent pneumatic compression devices. A change in the American

College of Chest Physicians 2012, 9th edition guidelines addressing perioperative management of antithrombotic therapy, is the recommendation of subcutaneous prophylactic dose UFH, or subcutaneous prophylactic or therapeutic dose LMWH as bridging therapy after valve replacement, rather than the traditional intravenous infusion of UFH.[246] This may be a concern as LMWH cannot be reversed in the setting of sudden bleeding.

New oral anticoagulants

There are several newer oral anticoagulants, sometimes referred to as novel oral anticoagulants, on the market. The most commonly used agents in the cardiac surgery population are dabigatran, rivaroxaban, and apixaban. Much of the rationale behind the development of these agents was to replace the vitamin K antagonist warfarin, which requires close monitoring of levels. The direct thrombin inhibitor dabigatran has the ability to inactivate clot bound thrombin, which heparin cannot do.[247] Direct thrombin inhibitors are antithrombin independent, and their sites for binding thrombin are not masked by fibrin, as seen in heparin. This is an important feature because clot bound thrombin is a stimulant of thrombogenesis. Dabigatran is FDA approved for stroke prevention in patients with AF. It has also been used for VTE prevention after hip and knee replacement, but these other indications are not currently FDA approved.

Initially, there was interest in using dabigitran as a warfarin alternative in patients with mechanical heart valves, as monitoring the international normalized ratio is not required, as in warfarin administration. The results of The Randomized, phase II study to Evaluate the sAfety and pharmacokinetics of oraL dabIGatran etexilate in patients after heart valve relpacemeNt trial demonstrated that the drug was not safe in this population.[248] In this trial, patients with mechanical aortic or mitral valves implanted in the last 7 days were randomized to either dabigatran or warfarin. The trial was stopped early because of reports of excess thromboembolic and bleeding events in the dabigatran arm. This study, as well as anecdotal reports, has led clinicians to believe that new oral anticoagulants are associated with more bleeding events. In November 2012, the FDA issued the statement that bleeding rates did not seem to be any higher for dabigatran users as compared with warfarin users when either drug was used for the first time.[249] This statement was in line with the randomized evaluation of long-term anticoagulant therapy trial which compared dabigatran with warfarin in patients with AF, and found that the 2 drugs carried a similar risk of bleeding.[250]

Despite the FDA statements and supporting medical literature, there is still apprehension in the cardiac surgery community surrounding the use of novel oral anticoagulants in the perioperative period, owing to the lack of a reversal agent. A case report by Wanek and colleagues[251] claims the safe and effective use of hemodialysis for dabigatran clearance before cardiac surgery, but this has not been studied in clinical trials. The use of new oral anticoagulants is further limited by the fact that they are not recommended in patients with renal or hepatic failure. An antidote for dabigatran, called aDabi-Fab, is currently in development and has been shown to bind the drug in a way similar to the way thrombin binds to it.[252] It is made of humanized dabigatran-specific (Fab) antibody fragments, which work in a similar fashion to those used to treat digoxin toxicity. The antidote was shown to completely reverse the anticoagulation of dabigatran in a rat model.[252] Further studies regarding the safety and efficacy of this antidote in humans are awaited.

The factor Xa inhibitors rivaroxaban and apixaban have also been designed not to require routine monitoring, with the aim of making them a more desirable choice than warfarin. Rivaroxaban is FDA approved for VTE prophylaxis after hip and knee surgery, risk reduction for VTE occurrence in those with current VTE, treatment of VTE, and for risk reduction of stroke in nonvalvular AF. Apixaban is FDA approved for the treatment of nonvalvular AF. It has also been used off-label for deep vein thrombosis prophylaxis after hip or knee replacement surgery, but is currently not FDA approved in this setting. Currently, there is no reversal agent for either of these drugs, but there is an antifactor Xa antidote currently in development. The agent, called

r-Antidote PRT064445, is a catalytically inactive, truncated form of factor Xa that does not bind to cell membranes.[253] It binds to factor Xa inhibitors at subnanomolar affinity. The antidote has been tested, and it was able to reverse the effects of factor Xa inhibitors in clotting tests in vitro and restore hemostasis of a liver laceration in a rat model.[253]

Thrombocytopenia and a summary of heparin-induced thrombocytopenia

Many patients experience thrombocytopenia in the period following CPB. A decrease in the platelet count of 40%-50% in the first 72 hours after cardiac surgery occurs in almost all patients.[254] This is thought to be due to the exposure of blood to the CPB circuit. It is difficult to distinguish the patient with an expected reduction in platelet count from a patient who has developed heparin-induced thrombocytopenia (HIT). Studies have shown that 25%-70% of patients will develop antiplatelet factor 4 heparin antibodies as detected by immunoassay, and 4%-20% will test positive by platelet activation assay in the first 10 days after cardiac surgery.[255-259] Only a small number of these patients will go on to develop clinically significant HIT. Although it is not universal, it seems that a secondary reduction in the platelet count that occurs 5-10 days after cardiac surgery is highly predictive for HIT.[260] Thrombocytopenia in the first 72 hours after cardiac surgery is usually caused by factors other than HIT, even when results of antibody tests are positive.[260,261] This information may dissuade clinicians from ordering antibody testing in the first 72 hours after surgery to avoid confusing the clinical picture with a positive test. Warkentin has also proposed a system to estimate the probability of a patient having HIT using what he calls "The Four T's."[262] The system includes using **T**hrombocytopenia, **T**iming of drop in platelets or other signs of HIT, **T**hrombosis, and o**T**her causes of a drop in platelet count to create a scoring system that predicts the probability of a patient being diagnosed with HIT.[262]

Testing for HIT includes the serotonin release assay (SRA), the heparin-induced platelet aggregation test, and the solid phase enzyme-linked immunosorbent assay immunoassay. The carbon 14 (^{14}C)-SRA is still the gold standard for diagnosing HIT.[263] This test has been studied in a prospective randomized trial and has a sensitivity and specificity of more than 95% when performed by an experienced laboratory technician.[264-266] The platelet aggregation assay, which is usually faster than the SRA, has better than 90% specificity, but lacks sensitivity.[267] The solid phase enzyme-linked immunosorbent assay immunoassay is not a functional assay like the other 2 tests. The test has a sensitivity of 91%-97%, meaning a negative result of the test is a strong indicator that a patient does not have HIT, but its positive predictive value varies.[268] The clinical utility of this test is yet to be determined.

Once HIT has been diagnosed, all heparin products, including heparin-coated catheters, must be withdrawn. Owing to the risk of thrombosis associated with the disease, patients must be anticoagulated. Initial anticoagulation should be obtained with continuous IV infusion. The IV direct thrombin inhibitor bivalirudin is FDA approved in patients with, or at risk of, HIT who are undergoing PCI. Although it is used in other populations, it is not FDA approved in other populations. The IV direct thrombin inhibitor argatroban is FDA approved for prophylaxis and treatment of HIT in all populations, but dosing should be adjusted in patients with heart failure, multiorgan failure, anasarca, liver dysfunction, and in patients after cardiac surgery. A transition to warfarin, with an international normalized ratio goal of 2-3 should only happen once the patient has been stably anticoagulated with a thrombin-specific inhibitor, and has a platelet count that is at least 150,000 per μL, at which time a minimum of 5 days of overlap should take place before the thrombin inhibitor is discontinued.[269-271] There is no specified length of therapy. There is a high risk of thrombosis in the 30 days after diagnosis of HIT; therefore, therapy should be continued past that time, and for 3-6 months if a thrombotic event has already occurred.[272-274]

Blood transfusion

Historically, patients with a hemoglobin level of less than 10 g/dL, or a hematocrit less than 30% were given a transfusion of packed red blood cells. This meant that many patients undergoing

cardiac surgery were receiving blood transfusions. Of all blood transfusions in the United States, 20% were associated with cardiac surgery, with 13% of those going to patients undergoing combined CABG and valve replacement surgery.[275,276] Newer research has shown that blood transfusion in the perioperative period actually has deleterious effects. Blood transfusion has been associated with a decrease in survival rates, with some studies citing up to a 70% increase in late mortality.[277,278] There are no prospective randomized trials in cardiac surgery patients on this topic; however, a randomized trial in critical care patients found that transfusion was associated with a higher in-hospital mortality rate, and that using a transfusion trigger of hemoglobin < 7 g/dL was associated with an increase in survival over a transfusion trigger of hemoglobin < 10 g/dL.[279] A large, multicenter study sought to determine whether an effort by all participating institutions to reduce the use of blood products would affect postoperative events after cardiac surgery, and whether perioperative transfusion influenced risk-adjusted outcomes.[280]

A blood product use protocol was put into place across all institutions for a period of 2 years for nonemergency, isolated CABG patients. The protocol used an intraoperative hemoglobin < 6 g/dL, or a hematocrit $< 18\%$, and a postoperative hemoglobin < 7 g/dL, or hematocrit $< 21\%$ as transfusion triggers. The patient also needed to have 1 of 4 clinical signs of decline to receive transfusion (Table 20).

LaPar and colleagues[280] demonstrated that implementing such a protocol improved postoperative morbidity, mortality, and resource utilization, and decreased adverse post-operative events and health care costs. Importantly, there were also significant cost reductions because of the conservation initiative. Over the 2-year study period, the total hospitalization costs were reduced by $49 million dollars statewide, with a median reduction of $4000 per patient hospitalization.[280]

Institutions have been slow to adopt this new way of thinking. The current STS and Society of Cardiovascular Anesthesiologists clinical practice guidelines give a few recommendations: patients who have lost more than 1500 mL or more than 30% of total blood volume should receive blood transfusion regardless of hemoglobin or hematocrit. Patients with chronic cardiovascular or pulmonary disease, or hemoglobin less than 7 g/dL (or < 6 g/dL if on CPB) should receive transfusion. Patients with hemoglobin level greater than 10 g/dL fare worse when given blood, and there is no clear benefit to transfusing at a threshold of a hemoglobin level of 7 g/dL vs 10 g/dL.[281,282] Despite this current research, only 20% of programs have actually even acknowledged these guidelines.[283]

Infectious disease

The nosocomial infection rate in cardiac surgery is unclear, as some reviews have cited rates between 10% and 20%, but the STS data report from 2013 has a much lower incidence of septicemia, pneumonia, and mediastinits.[194] Bacteremia due to central line–related blood stream infections (CLABSI), urinary tract infections due to catheters, and *C. difficile* colitis are not specifically reported in the STS database, but are an important source of morbidity and mortality in all critically ill patients. Our review focuses on ventilator-associated events (VAEs) and mediastinitis, which are the 2 infections with the greatest morbidity.

Table 20
Clinical signs favoring blood transfusion[280]

Intraoperative triggers	Postoperative triggers
1. Low oxygen saturation (< 60 mm Hg)	1. Elevated oxygen requirement
2. Lactate > 2.2 mmol/L	2. Systemic hypotension
3. Base deficit > 3 mEq/L	3. Evidence of end-organ dysfunction
4. Serum bicarbonate < 22 mEq/L	4. Evidence of persistent bleeding

Ventilator-associated events

One of the most significant complications of cardiac surgery is postoperative pneumonias, which is associated with longer length of hospitalization, and associated mortality rate between 20% and 49%.[284,285] The incidence of postoperative pneumonia is 2.8% in isolated CABG, 2.4% in isolated AVR, and 4.3% in combined AVR-CABG cases.[2] A recent attempt has been made to identify patients who will develop pneumonias postoperatively, with a risk scoring system, but it was not used extensively.[286] Another recent change is the diagnostic classification of ventilator-associated pneumonia (VAP), which has changed to VAC, owing to concern over the subjectivity involved in making the diagnosis.[285] All pneumonias after operation are not VAEs, but our discussion focuses on this branch of pneumonias because of its high mortality, and recent important change in definition.

A surveillance algorithm now exists, provided by the Centers for Disease Control, in which patients can have a VAE that could be infectious and is then known as an infectious VAC.[287] Ventilator-associated conditions are associated with increased ICU length of stay, increased length of mechanical ventilation, but not increased ICU mortality in a study.[288] Another study retrospectively applied the VAC definition to a prospective VAP study and determined that VACs are associated with significant morbidity and mortality, but VAP had poor correlation with VAC.[289] Yet, the ventilator bundle used to reduce VAPs also lead to a decrease in VACs. Although acronyms are confusing, it is important for cardiac surgery programs to be aware of VAE, as these are reported publically. More importantly, the condition has adverse effects on critically ill patients. Ventilator bundles are still followed, along with ventilator-weaning protocols. Both of these measures are important in cardiac surgery patients to decrease time to extubation.

Mediastinitis

Deep sternal wound infection, or mediastinitis, occur in 0.2% of isolated AVR patients, 0.3% of isolated CABG patients, and 0.3% of combined CABG-AVR procedures.[2] In-hospital mortality rates vary between 10% and 47%, and in a retrospective case–control series of 18,532 CABG patients, this infection decreased 10-year survival significantly.[290] Often, bacteria do not grow, but the 2 most common organisms implicated are *Staphloccocus aureus* and *Staphylococcus epidermidis*.[290,291] Risk factors for mediastinitis include diabetes, excess blood transfusions, active smoking, obesity (body mass index $>30 \text{ kg/m}^2$), COPD, prolonged CPB time, reoperation, prolonged intubation time, surgical re-exploration, and the use of bilateral internal mammary arteries.[194,290,292] Efforts to prevent surgical site infections have benefited from the use of preoperative antibiotics within 60 minutes before surgery, with the use of broad-spectrum antibiotics for patients with methicillin-resistant *S. aureus*.[293] The prevention of methicillin-resistant *S. aureus* is a priority, and institution-specific protocols have been developed. Best practices have been recommended by the ACC Foundation-AHA, and include reduction of postoperative infections, use of perioperative antibiotics, insulin infusion to keep the glucose level less than 180 mg/dL, and the use of leukocyte-reduced blood when transfusion is necessary.[194]

Catheter-associated or central line–associated and C. difficile infections

Hospital-acquired infections are both costly and lethal. In a 2-institution retrospective review of 8405 cardiac surgery patients over 7 years, *C. difficile* infection had an incidence of 0.79%.[294] The diagnosis of *C. difficile* infection was associated with a longer ICU and overall hospital stay, but no difference in 30-day mortality rate.[294] Both urinary tract infections due to catheters and CLABSI cause significant health burdens, as CLABSI alone have been implicated in costing the United States health care system anywhere between $960 million and $18.2 billion. Although associated mortalities and morbidity exist, and their incidence is difficult to assess, the amount of hospital-acquired infections are publically reported quality indicators. This reporting serves as a stark

reminder to cardiac surgery programs that the complications of postoperative care are publically reported, are costly, and, most importantly, can negatively affect their patient's outcomes.[295]

Nutrition

Preoperative evaluation of nutritional status has not been well defined. Historically, nutritional status has been studied using the serum albumin concentration. This may not be an entirely accurate marker, as it has a long half-life, is affected by hydration and renal function, and is not reflective of recent nutritional changes.[296] By contrast, the serum prealbumin concentration is not affected by hydration and has a short half-life. A recent study by Yu and colleagues[296] evaluated the use of the prealbumin level in patients undergoing cardiac surgery and found that patients with a level ≤ 20 mg/dL had an increased risk of postoperative infection, and a need for longer mechanical ventilation. These results indicate that it may be prudent to maximize a patient's nutritional support before cardiac surgery.

Critically ill patients are often in a catabolic state, and suboptimal feeding will eventually have negative effects on a patient's condition. Historically, total parenteral nutrition was used to provide a patient with nutrition when the gut could not be used. Current research has shown that the use of total parenteral nutrition is a strong predictor of candidemia and that avoiding its use is protective against developing this infection.[297] It is commonly thought that postpyloric feeding is the answer to this problem and that patients will be able to tolerate higher volumes of enteral feeding, as well as have a reduced incidence of VAP from aspiration. A prospective, randomized, controlled trial found that mechanically ventilated patients receiving nasogastric feeding, who had elevated gastric residuals, did not have a reduction in pneumonia, when early nasojejunal feeding was used.[298] Furthermore, these patients did not experience an increase in the level of energy delivery.[298] Trophic or "trickle" feeding is often used in the critical care setting. This has been studied in a large randomized trial of medical patients with ALI, a population with many characteristics seen in the cardiac critical care setting. The EDEN randomized trial (initial trophic vs full enteral feeding in patients with ALI) found that in patients with ALI, some of whom were also receiving vasopressors, initial trophic enteral feeding for as many as 6 days did not improve ventilator-free days, mortality rate at 60 days, or infectious complications, but was associated with a decrease in gastric intolerance.[299] The study did not show an increase mortality in either group, which points toward early feeding, either trophic or full enteral, in a critical care population.

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